NASA Technical Memorandum 101451

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(NASA-TM-101451) SOME COMPOSITE BEARING AND SEAL MATERIALS FOR GAS TURBINE APPLICATIONS: A REVIEW (NASA) 15 p CSCL 11A

N89-14338

Unclas
G3/27 0185337

Harold E. Sliney
Lewis Research Center
Cleveland, Ohio

Prepared for the
34th International Gas Turbine and Aeroengine Congress and Exposition
sponsored by the American Society of Mechanical Engineers
Toronto, Canada, June 4–8, 1989

NASA

SOME COMPOSITE BEARING AND SEAL MATERIALS FOR GAS TURBINE APPLICATIONS - A REVIEW

Harold E. Sliney
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

E-4561

ABSTRACT

A review is given of the selection and tribological testing of materials for high-temperature bearings and seals. The goal is to achieve good tribological properties over a wide range of temperatures because bearings and seals must be functional from low temperature start-up conditions on up to the maximum temperatures encountered during engine operation. Plasma sprayed composite coatings with favorable tribological properties from 25 to 900 °C are discussed. The performance of these coatings in simple tribological bench tests is described. Examples are also given of their performance in high-speed sliding contact seals, as Stirling cylinder liner materials, and as back up lubricants for compliant foil gas bearings.

INTRODUCTION

As gas turbine engine designs become more complex, the need for high-temperature bearing and seal materials increases. For example, many modern gas turbine engines contain variable stator vanes (VSV) in the compressors (see Fig. 1). These vanes are nonrotating, but their angle of attack or pitch is variable. Each vane requires two sliding contact pivot seals that are basically cylindrical bearings with a thrust collar. In the downstream stages of the compressor, gas temperatures can be on the order of 540 °C and the pivot seal material temperature is about 370 °C (700 °F). A high temperature polyimide polymer with graphite fiber/fabric reinforcement is a material of choice for this application. This material was chosen after the results of extensive laboratory research at several laboratories, which demonstrated its favorable tribological properties, were reported (e.g., Giltrow and Lancaster, 1968; Sliney et al., 1972, 1975, 1979; Fusaro and Sliney, 1978; Gardos and McConnell, 1982). Engine performance could be further improved by also employing variable stator vanes in the turbine section. Turbine VSV components will require self-lubricating pivot materials capable of operating at much higher temperatures, possibly up to 1500 °C. This of course, is well beyond the thermal capabilities of polymer composites. Satisfactory materials for turbine VSV bushings must have very good thermochemical stability and have sufficiently low friction and wear to allow actuation with modest forces and to provide adequate durability. The well known graphite and molybdenum disulphide (MoS_2) solid lubricants are oxidatively unstable in air above about 300 °C for long duration applications and in some cases, can possibly be used at higher temperatures for a short duration (Sliney 1982). The oxidation rate of carbon/graphite can be reduced by formulating the graphite with oxidation-inhibiting additives (Wedeven and Harris, 1987). The maximum service temperature in air for formulated long-life carbon/graphite components in generally accepted to be about 500 °C and certainly no higher than 677 °C.

For even higher temperature applications, more novel solid lubricating materials are needed. The materials must be chemically stable at high temperatures and must also have the physical properties needed to make them lubricative. The scope of this paper encompasses: (1) a discussion of the selection of such materials; (2) the formulation of self-lubricating plasma sprayed composite coatings with wide temperature spectrum capability; (3) the basic friction and wear of these composites, and (4) examples of prototype applications.

MATERIALS SELECTION

A solid lubricant material for high temperature use must have good thermochemical stability, a stable crystal structure over the temperature range of interest, and an adequately high melting point. Solid lubricant coatings should be formulated to have a thermal expansion coefficient that reasonably matches the intended substrate in order to prevent spalling during temperature excursions. Important properties of solid lubricants in general are: they are soft; they have a high degree of plasticity (the plasticity must be associated with a low yield strength in shear for lubricity); and they must adhere tenaciously to the lubricated surfaces because the material cannot perform a lubricating function if it is not retained within the sliding interface.

We have used calcium fluoride, barium fluoride, and silver as solid lubricants in our high temperature

coatings. They satisfy the chemical and physical criteria over specific ranges of temperatures. Thermochemical calculations indicate that these materials should be chemically stable to high temperatures in air or in hydrogen and this has been experimentally verified. The hardness-temperature characteristics of these two fluorides and of metallic silver were reported by Deadmore and Sliney (1987) and are given in Fig. 2(a). Silver is very soft at room temperature with a hardness of about 30 kg/mm^2 and this continuously decreases to about 4 kg/mm^2 at 800 °C. Thin films of silver lubricate quite well at temperatures up to about 500 °C, but appear to have inadequate film strength to support a load at higher temperatures. The fluorides, on the other hand, are considerably harder than silver at the lower temperatures, but their hardness drops off rapidly with temperature and at about 400 °C, their hardnesses are 30 kg/mm^2 or less. Also, brittle to ductile transition temperatures, at high strain rates, of 300 to 400 °C have been reported for these fluorides (Phillips, 1961; Burn and Murray, 1962; Liu and Li, 1964). Fluoride coatings have been shown to be lubricious above 400 °C, but ineffective as lubricants at lower temperatures (Sliney, 1986). Therefore, there is an apparent correlation of hardness-temperature characteristics and of the brittle to ductile transition temperature with the friction-temperature characteristics.

Since silver films are lubricative at the lower temperatures and the fluorides discussed are lubricative at higher temperatures than silver, it is reasonable that a composite coating containing silver and the fluorides might be lubricious over a wide temperature range, and this has been demonstrated repeatedly in our research (Sliney, 1979, 1986). Figure 2(b) illustrates this point. The friction-temperature characteristics of 0.02 mm thick fused fluoride coatings with and without silver, which were prepared by a process similar to porcelain enameling are compared. The data were obtained with a pin-on-disk tribometer illustrated in Fig. 3. The all-fluoride coatings were lubricious only above about 400 °C while the coatings that also contained silver lubricated from room temperature to 800 °C. These results with relatively thin coatings were followed by research with thicker plasma sprayed coatings.

PLASMA SPRAYED COATINGS

We have reported two series of plasma sprayed coatings containing fluoride solid lubricants: the PS100 and the PS200 series (Sliney, 1979; DellaCorte and Sliney, 1987). The PS100 series contains stable fluorides and silver with a nichrome binder; the PS200 series contains the same lubricants and chromium carbide with a nickel-cobalt alloy binder. The proportions of the components can be varied to optimize the coatings for various uses. In general, coatings in the PS100 series, which are softer, have been useful in applications where a slightly compliant, but nongalling coating is needed. One example of this type of application is a knife edge high speed shaft seal. In this type of seal, circumferential raised knife edges on the shaft slide against a coated seal housing. Thermal expansion or run-out causes the knife edges to contact and deform the coating to provide a seal. This seal material is conformable and relatively dense rather than abradable, and therefore minimizes secondary leakage compared to that which occurs through porous abradable seals. The PS100 coating is also much more resistant to erosion by particulates carried in the gas path. The wear coefficient, k, for the PS100 series of coatings is on the order of 10^{-5} mm^3/Nm (moderate wear regime) and the friction coefficient is typically 0.21 to 0.25.

When more wear-resistant coatings are needed, the PS200 series is preferable. The PS200 concept is summarized in Fig. 4. As the sketch indicates, the coating is a composite material with the lubricating solids distributed throughout a wear-resistant chromium carbide/nickel alloy matrix. A typical composition consists of 10 wt % each of silver and calcium fluoride/barium fluoride eutectic in the metal-bonded chromium carbide matrix.

FRICTION AND WEAR OF PS200 PLASMA SPRAYED COATINGS

The wear and friction of PS200 coatings in sliding contact with Stellite 6B, a cobalt-chromium base alloy, in three different atmospheres: air, helium, and hydrogen, are given in Figs. 5 and 6 (from DellaCorte and Sliney, 1988). Tests in hydrogen give the lowest friction and wear. Friction coefficients are typically 0.23±0.05. Coating wear factors (k) are about 6×10^{-6} mm^3/Nm and pin wear factors are in the 10^{-7} mm^3/Nm range. This is generally considered to be in the very mild to low wear regime. Friction and wear are moderately higher in helium and still higher in air. In general, friction and wear increase somewhat as the test atmosphere chemistry changes from reducing, to inert, to oxidizing. The maximum test temperature in these tests was 760 °C. We have shown elsewhere that the PS200 coating has potential applicability to 900 °C (Sliney, 1986). However, oxidative wear may limit coating durability in air above about 700 °C.

In addition to Stellite 6B, several other alloys were tested as counterface pin materials for sliding against PS200. The nominal chemical compositions of these alloys are given in Table I. However, none of them were as effective as Stellite 6B on PS200. This material combination was subsequently selected as a piston ring/cylinder liner material combination for evaluation in a Stirling engine in a "Hot Piston Ring" development program. The results of this program are summarized below.

APPLICATION TESTS OF PS200

Stirling Engine Cylinder Liner

The lubrication of the piston ring/cylinder contacts in the Stirling automotive engine is a challenging high-temperature tribological problem. Metal temperatures are as high as 600 to 1000 °C near the top of the cylinder walls. The working fluid in the engine thermodynamic cycle is hydrogen. The lubricant coating therefore, must not only provide low friction and wear, but also must be thermochemically stable in a strongly reducing hydrogen atmosphere.

In current designs of the Stirling engine, the piston rings are made of reinforced polytetrafluoroethylene (PTFE). They are located in ring grooves near the bottom of the piston where the temperatures are relatively low and do not degrade the PTFE. This arrangement results in a long annular "appendix" gap from the top of the piston to the piston ring. This gap is the source of parasitic energy losses (Tomazic, 1985). It is therefore desirable to minimize the appendix gap by locating the top ring in a groove near the top of the piston. A schematic of the ring locations in a conventional baseline piston and in a piston with an added top (hot) ring are shown in Fig. 7.

A Mechanical Technology Inc. (MTI) designed Stirling engine was modified to allow the use of hot piston rings. The cylinders were bored out to allow

for a PS200 coating thickness of 0.25 mm (0.010 in.) and the pistons were modified to accept the Stellite 6B piston rings. The coatings were sprayed on the cylinder walls to a thickness of about 0.35 mm (0.015 in.), then diamond ground to a final thickness of 0.25 mm. Engine tests reported by Sliney (1988) were run at a heater head temperature of 700 °C and 5, 10, and 15 MPa mean operating pressure over a range of operating speeds. Tests were run both with the "hot rings" in place and without them to provide a baseline for comparison.

At some operating conditions, efficiency as calculated from specific fuel consumption, increased slightly compared to the baseline engine. Under other conditions, no significant differences in efficiency were measured. The overall average indicated about a 3 percent increase in efficiency with the "hot rings" over the baseline configuration. This increase was over and above the additional friction loss introduced by the "hot rings." Seal leakage measurements showed a significant reduction in leakage with the "hot ring" in place. In addition, cylinder wall temperature measurements indicated less cylinder heating between the lower piston rings and the "hot ring." Approximately 22 hr of ring-on-coating operation were recorded. Figure 8 is a photograph of the coated cylinder wall after the engine test. The dark, polished surface is the area swept by the piston ring. The results of applying PS200 to the Stirling Engine cylinder walls are encouraging. Overall engine efficiency was improved and post-test wear measurements indicate that the coated engine components could have been run considerably longer, at least several hundred hours. This solid lubricated Stirling Engine test indicates a potential usefulness of long life, self-lubricating materials for improved engine and mechanism efficiency and for other high temperature applications such as gas bearings.

Gas Bearings

Figure 9 is a gas bearing journal coated with PS200 and finished by diamond grinding. Start-stop tests of this journal in a foil bearing were conducted in an air atmosphere using the test apparatus shown in Fig. 10 and reported by Wagner and Sliney (1986). The surface velocity and torque profiles during a typical start-stop cycle are shown in Fig. 11. The higher torque at the beginning and end of each cycle occurs during sliding contact when the surface velocity is below the critical lift-off velocity for the bearing. It is during these low operating speed periods that solid lubrication must be provided for the bearing. PS200 coatings on the journals provide this lubrication. Foil bearings with PS200 coated journals have routinely survived life tests in air consisting of 10 000 starts and stops (20 000 rubs) at bearing temperatures from 25 to 650 °C.

CONCLUDING REMARKS

This paper has reviewed some of the high temperature solid lubrication research performed at NASA Lewis Research Center that appears to be applicable to gas turbine technology. Some of the more significant considerations are the following:

1. For the high temperature requirements in gas turbine engines, conventional solid lubricants such as graphite and molybdenum disulphide do not have the required thermal-oxidative stability. It is proposed that selection criteria for new solid lubricants must include chemical stability at high temperatures, plasticity, low yield strength in shear, and low hardness.

2. Mixtures of calcium fluoride, barium fluoride, and silver have shown promise in thin fused coatings and in plasma sprayed coatings for lubricating from room temperature to at least 760 °C in hydrogen, helium, and air. Lubrication is more effective in hydrogen than in air, but the coatings have been successful in long term start-stop testing as air bearings at 650 °C. The maximum useful temperature of these coatings is estimated to be about 900 °C (just below the melting point of silver: 961 °C).

3. Plasma sprayed composite coatings of metal bonded chromium carbide, calcium fluoride/barium fluoride eutectic, and silver have been successful as seal and bearing lubricants in component testing under conditions considered to be relevant to gas turbine applications.

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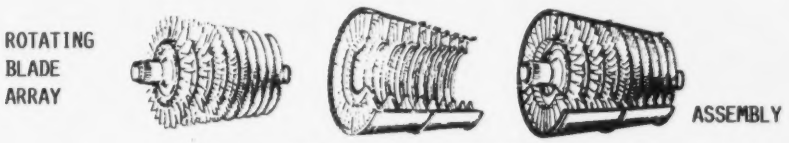
TABLE I. - NOMINAL COMPOSITION AND ROCKWELL HARDNESS OF CANDIDATE PISTON RINGS MATERIALS

[Compositions are taken from manufacturers' data; hardness values, at room temperature.]

Pin material	Element, wt %														Rockwell hardness
	Ni	Cr	Co	C	Fe	Al	Si	Ti	Mo	Mn	B	W	N	Cb	
Inconel X-750	70	16	1	0.1	7.5	1	----	2.5	----	1	---	-	----	---	R_C40
XF818	18	18	--	.2	54.6	-	0.3	---	7.5	.15	0.7	-	0.12	0.4	R_C18
Stellite 6B	2	30	59	1	1	-	.75	---	.75	1.25	---	4	----	---	R_C42
Nitronic 60	8	18	--	.1	61.8	-	4.0	---	----	.8	---	-	.12	---	R_C28



VARIABLE PITCH STATOR
VANE ARRAY

COMPONENTS AND ASSEMBLY OF AXIAL FLOW COMPRESSION

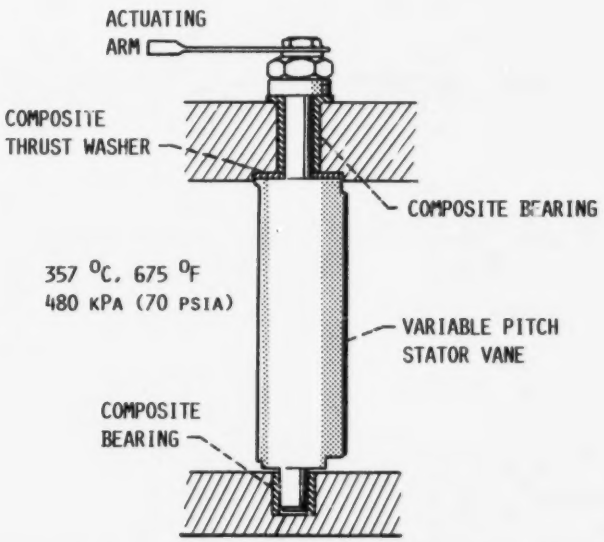
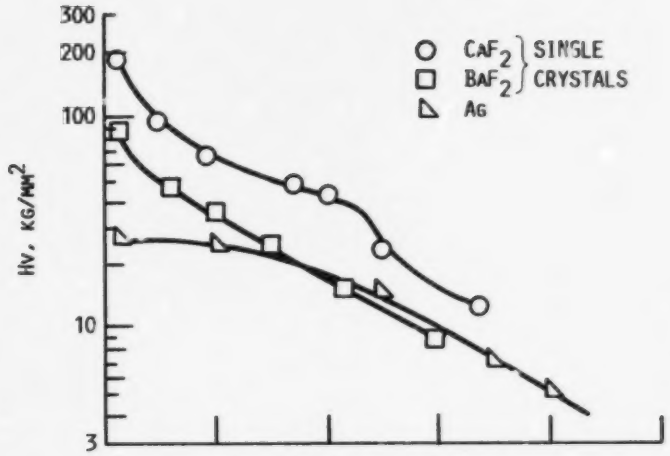
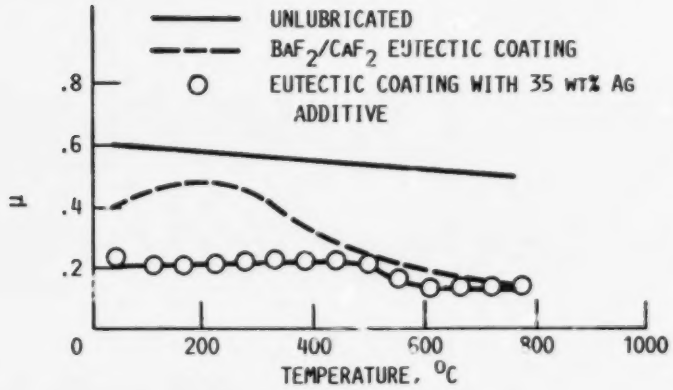


FIGURE 1. - APPLICATION OF POLYIMIDE COMPOSITE IN JET ENGINE COMPRESSOR.



(A) HOT HARDNESS.



(B) FRICTION.

FIGURE 2. - EFFECT OF TEMPERATURE ON MICROHARDNESS AND FRICTION COEFFICIENTS OF COATING MATERIALS.

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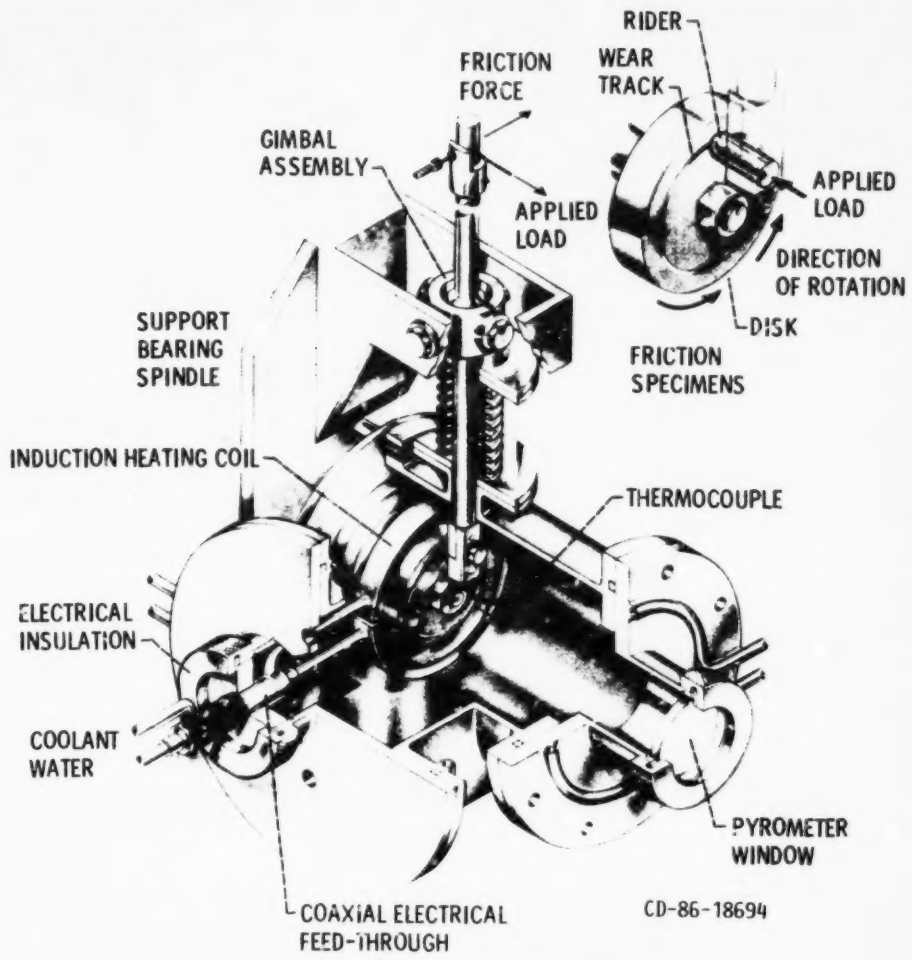

FIGURE 3. - PIN-ON-DISK TRIBOMETER.

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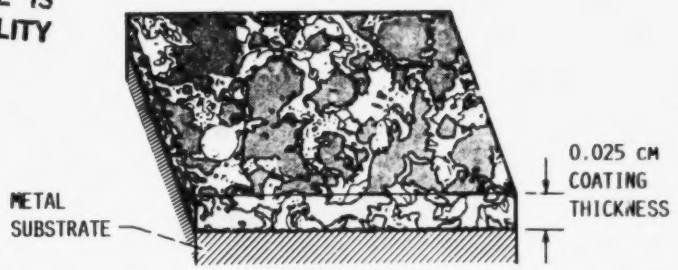

COMPOSITION	CHARACTERISTICS
32% Ni ALLOY 48% Cr_3C_2	WEAR AND OXIDATION RESISTANT METAL BONDED CARBIDE
10% Ag	LOW TEMPERATURE START UP LUBRICANT WITH HIGH TEMPERATURE OXIDATION RESISTANCE
10% BaF_2/CaF_2 EUTECTIC	HIGH TEMPERATURE LUBRICANT

- LUBRICATES IN AIR, HELIUM, OR HYDROGEN TO +900 ^{o}C

FIGURE 4. - CONCEPT OF PS200 - A PLASMA-SPRAYED COMPOSITE SOLID LUBRICANT COATING.

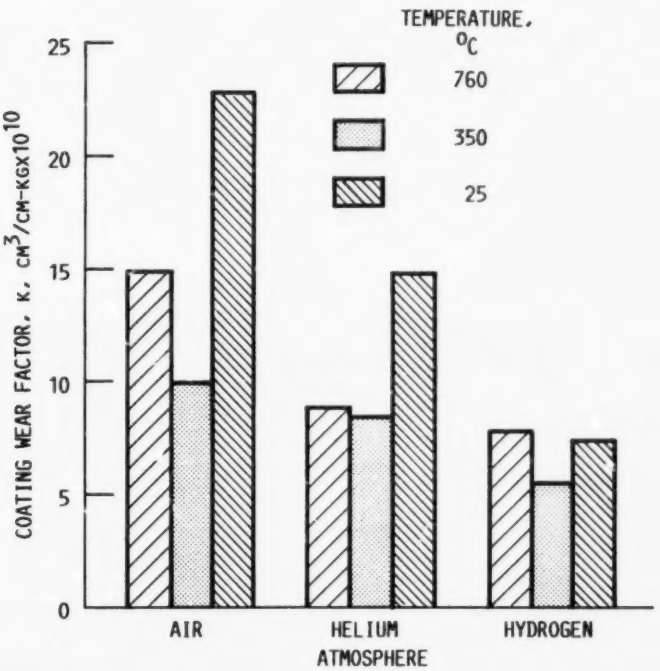

FIGURE 5A. - DISK COATING WEAR FACTOR, κ, FOR THE PS200 COATING IN VARIOUS ATMOSPHERES. TEST CONDITIONS: 2.7 m/s SLIDING VELOCITY, 38.97 kPa CHAMBER PRESSURE, 4.9 N NORMAL LOAD.

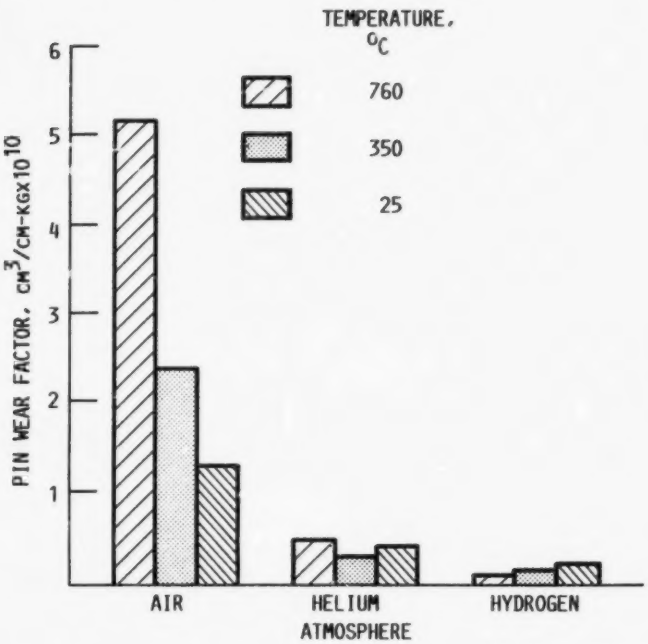

FIGURE 5B. - PIN WEAR FACTOR, κ, FOR THE HARDENED COBALT ALLOY TESTED AGAINST THE PS200 COATING IN VARIOUS TEST ATMOSPHERES. TEST CONDITIONS: 2.7 m/s SLIDING VELOCITY, 38.97 kPa CHAMBER PRESSURE, 4.9 N NORMAL LOAD.

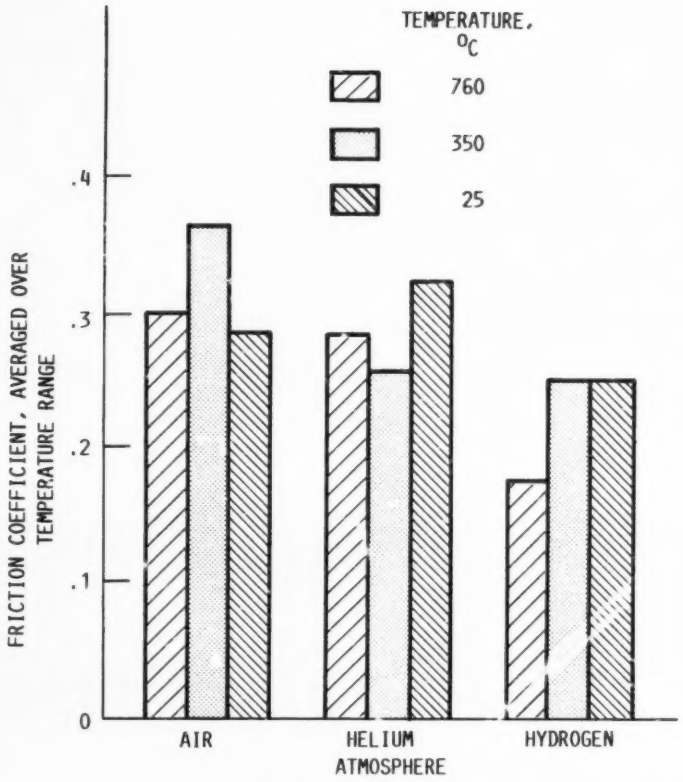

FIGURE 6. - FRICTION COEFFICIENT FOR PS200 SLIDING AGAINST HARDENED COBALT ALLOY IN VARIOUS ATMOSPHERES. TEST CONDITIONS: 2.7 m/s SLIDING VELOCITY, 38.97 kPa CHAMBER PRESSURE, 4.9 N NORMAL LOAD.

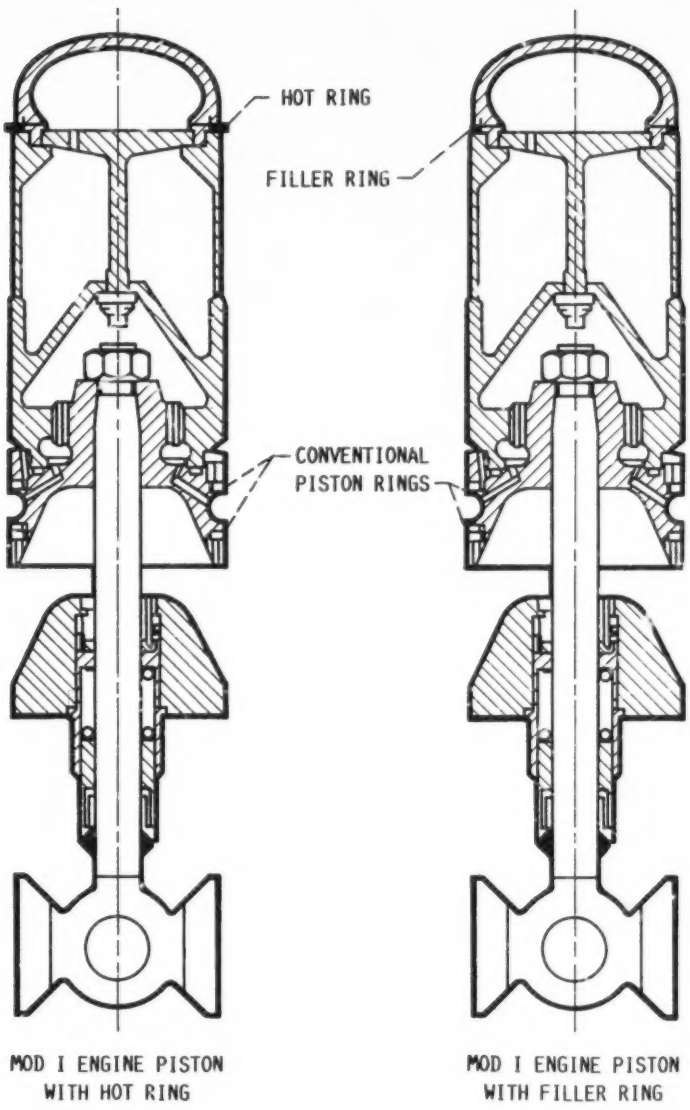

FIGURE 7. - PISTON CONFIGURATIONS.

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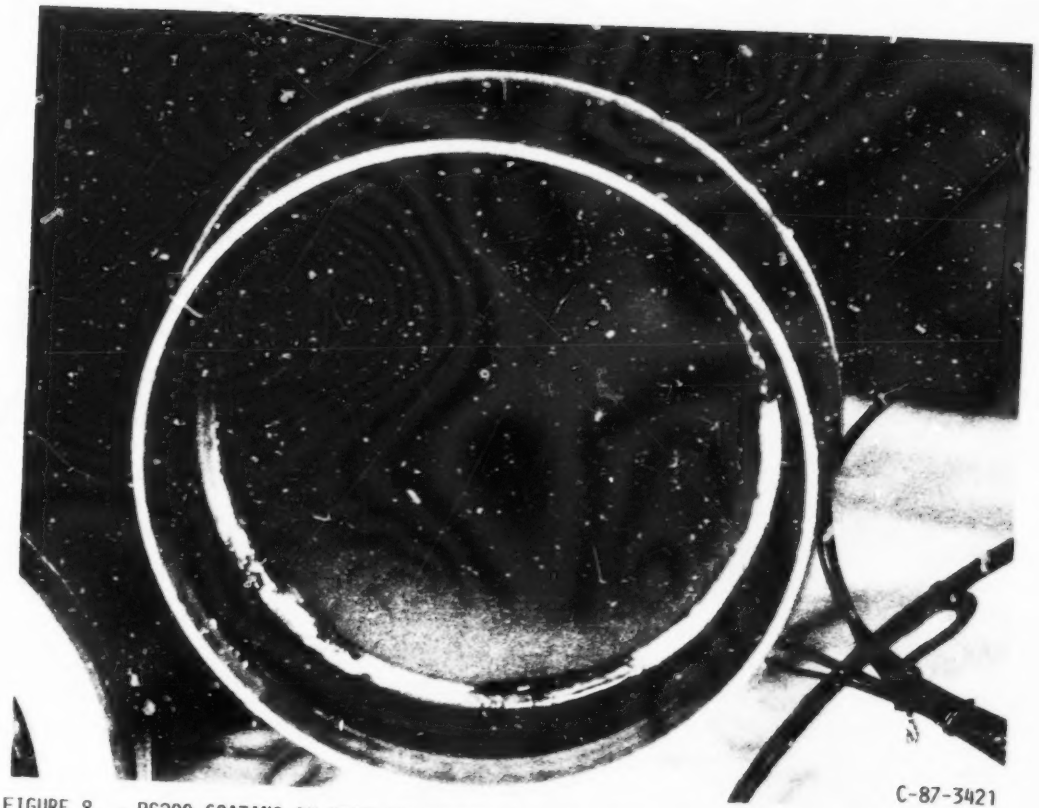

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FIGURE 8. - PS200 COATING ON STIRLING ENGINE CYLINDER AFTER 22-HOUR ENGINE TEST WITH "HOT-RINGS".

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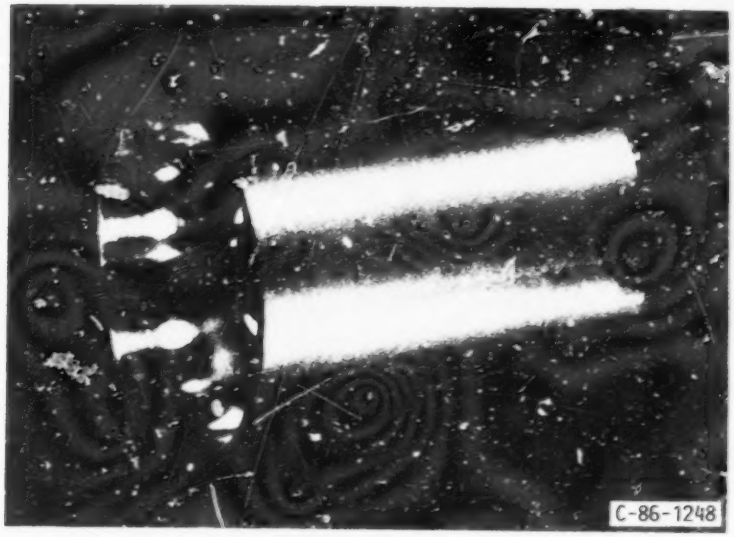

FIGURE 9. - GAS BEARING JOURNAL COATED WITH PS200 AND FINISHED BY DIAMOND GRINDING. (SUCCESSFULLY COMPLETED 10 000 START/ STOP RUBS IN A FOIL GAS BEARING AT TEMPERATURES UP TO 650 ^{0}C.)

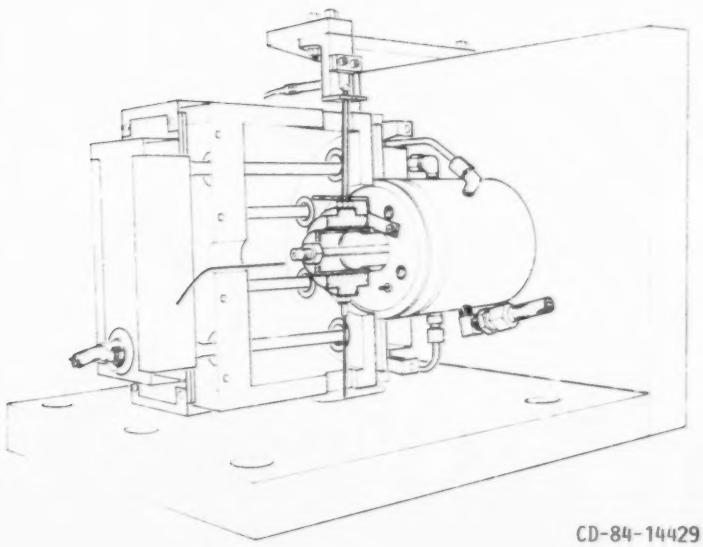

FIGURE 10. - FOIL BEARING TEST MACHINE.

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Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-101451		

4. Title and Subtitle

Some Composite Bearing and Seal Materials for Gas Turbine Applications – A Review

5. Report Date

6. Performing Organization Code

7. Author(s)

Harold E. Sliney

8. Performing Organization Report No.

E-4561

10. Work Unit No.

505-63-1A

9. Performing Organization Name and Address

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

11. Contract or Grant No.

13. Type of Report and Period Covered

Technical Memorandum

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, D.C. 20546-0001

14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the 34th International Gas Turbine and Aeroengine Congress and Exposition sponsored by the American Society of Mechanical Engineers, Toronto, Canada, June 4-8, 1989.

16. Abstract

A review is given of the selection and tribological testing of materials for high-temperature bearings and seals. The goal is to achieve good tribological properties over a wide range of temperatures because bearings and seals must be functional from low temperature start-up conditions on up to the maximum temperatures encountered during engine operation. Plasma sprayed composite coatings with favorable tribological properties from 25 to 900 °C are discussed. The performance of these coatings in simple tribological bench tests is described. Examples are also given of their performance in high-speed sliding contact seals and as Stirling cylinder liner materials, and as back up lubricants for compliant foil gas bearings.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Solid lubricant; Tribological coatings; High temperature tribology; Friction control; Wear control	Unclassified – Unlimited Subject Category 27

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of pages	22. Price*
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